Quantum Interference of Particles and Resonances

Yakov Azimov
(PNPI)

JLab Seminar, September 12, 2008

When looking at the Maxwell equations,
it is hard to imagine how beautiful the rainbow is.

R. P. Feynman (*cited from memory*)

Similar may be said about **Quantum Interference**

Everybody knows
that the interference does exist.
But it is not always easy to imagine
how it will work in a particular case.

Let us begin from the beginning

- **Quantum physics** is probabilistic.
- **Classical physics** can be probabilistic as well (Statistical physics).
- **Essential difference:**

  Classical Phys. adds probabilities;

  Quantum Phys. adds amplitudes.
- **Important consequence:**

  possibility of **interference** effects;

  various wave functions may **mix.**
- **Impressive result:**

  particles may **oscillate** in time, transforming to each other.

The most famous examples:

- strangeness oscillations –

  in decays of neutral *K*-mesons (at *~10 cm*),
- beauty oscillations –

  in decays of neutral *B*-mesons (at some μm)

  [coherent oscillations of several flavors are also possible

  Ya.A., PR D42 (1990); EPJ A4 (1999)],
- neutrino oscillations (up to hundreds *km* , MINOS

  or even astronomical distances ! solar ν)

A wide variety of macroscopic distances !

Quite **macroscopic** manifestations of quantum **microscopic** effects !

Let us consider in more detail the time dependence in decays of neutral kaons

Neutral kaons decay as a coherent mixture of the **short**-lived K_S and the **long**-lived K_L.

$\tau_S = 0.9 \cdot 10^{-10}$ ***s ;***
$\tau_L = 5.1 \cdot 10^{-8}$ ***s***

At **small** times, the final state 2π comes mainly from K_S (K_L/K_S amplitude ratio is $2 \cdot 10^{-3}$).
At very **high** times, when K_S died, only K_L provides 2π.

no inter-ference

Interference for $K_S, K_L \to 2\pi$ is well seen only in the transition region, after several τ_S .

Interference may depend on the decay mode

Non-universality **!**

For semileptonic decays the interference seen from the initial moment till K_S dies.

K_S, K_L amplitudes are nearly the same, up to sign.

Hadronic resonances may also mix

and oscillate in time -

evolution of $\rho^0, \omega \to \pi^+\pi^-$ is similar to $K_S, K_L \to \pi^+\pi^-$:

ρ^0 is **shorter**-lived, decay $\omega \to \pi^+\pi^-$ is **weaker**

(**isospin** suppression for ω , **CP**-suppression for K_L).

But it is **unobservable**,

because of **too short** lifetimes:

$$\tau < 10^{-20}\ s, \quad c\tau < 3 \cdot 10^{-10}\ cm$$

[compare $\tau_S = 0.9 \cdot 10^{-10}\ s, \quad c\tau_S = 2.7\ cm$]

However, the same phenomenon may be **seen** in the complementary variable - energy (mass in the rest frame):

it is seen here as deformation of Breit-Wigner peaks.

- The pure BW term $\left|a \cdot (E - E_0 + i\,\Gamma/2)^{-1}\right|^2$

$$= |a|^2 \cdot [(E - E_0)^2 + \Gamma^2/4]^{-1} \;;$$

may **depend** on ***E***

- BW with background $\left|B + a \cdot (E - E_0 + i\,\Gamma/2)^{-1}\right|^2$

$$= |B|^2 + |a|^2 \cdot [(E - E_0)^2 + \Gamma^2/4]^{-1}$$

interference term

$$+ [\, 2|B\,a| \cdot \cos\varphi \cdot (E - E_0) + |B\,a| \cdot \sin\varphi \cdot \Gamma \,] \times [(E - E_0)^2 + \Gamma^2/4]^{-1}$$

role of the interference depends on the relative **value** and on the relative **phase** φ of ***B*** and ***a*** ; it is **linear** in ***a***, may change **sign** and be either **positive** or **negative**

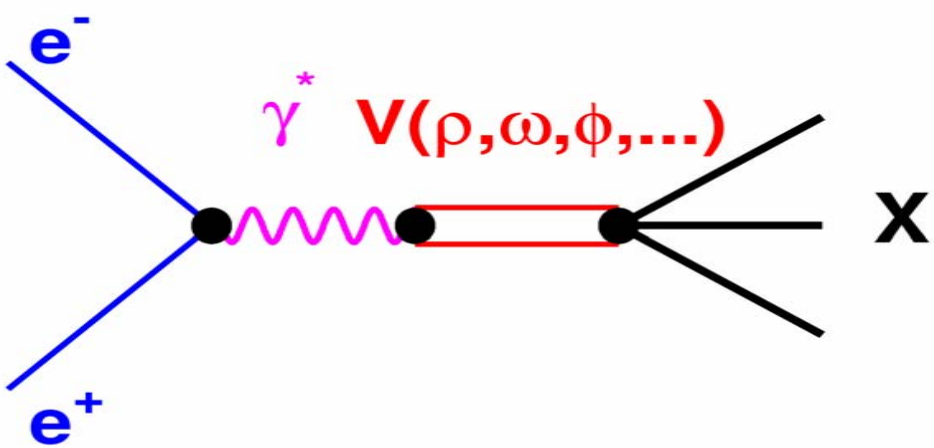
Intermediate conclusions (1)

- At a small value of $|a/B|$
  the interference term may be more essential
  than the proper BW contribution.
- Due to additional E-dependence,
  the interference may change sign,
  provide either **bump**, or **dip**, or both.
- The bump and/or dip **positions** are,
  in general, **shifted** from the true position
  of the resonance.
- The same resonance may interfere differently
  in different decay modes.

A rich source of examples,
how the **interference** works,
is provided by the reaction

$e^+ e^- \rightarrow$ hadrons

Contributions with the same final state are **coherent**; they all are produced through γ / Z and may directly interfere, if have the same decay mode



Independent contribution of a resonance is a BW-peak, proportional to $\Gamma_{ee} \cdot \Gamma_X / \Gamma_{tot}$;
interference may change its form and intensity

$\Gamma(\rho)$ = 149.4 MeV; $\Gamma(\omega)$ = 8.5 MeV; $\Gamma(\phi)$ = 4.3 MeV

$\Gamma(\omega \to 3\pi)$ = 7.58 MeV
$\Gamma(\rho^0 \to 3\pi)$ = 0.015 MeV **isospin violated**
$\Gamma(\phi \to 3\pi)$ = 0.65 MeV **Zweig rule violated**

Bkg near ϕ changes slowly

↓

nearly standard interference curve, instead of ϕ –peak: both **bump** and **dip**, each has the **form** different from BW; **max/min** different from the ϕ -mass

hep-ex/0604051

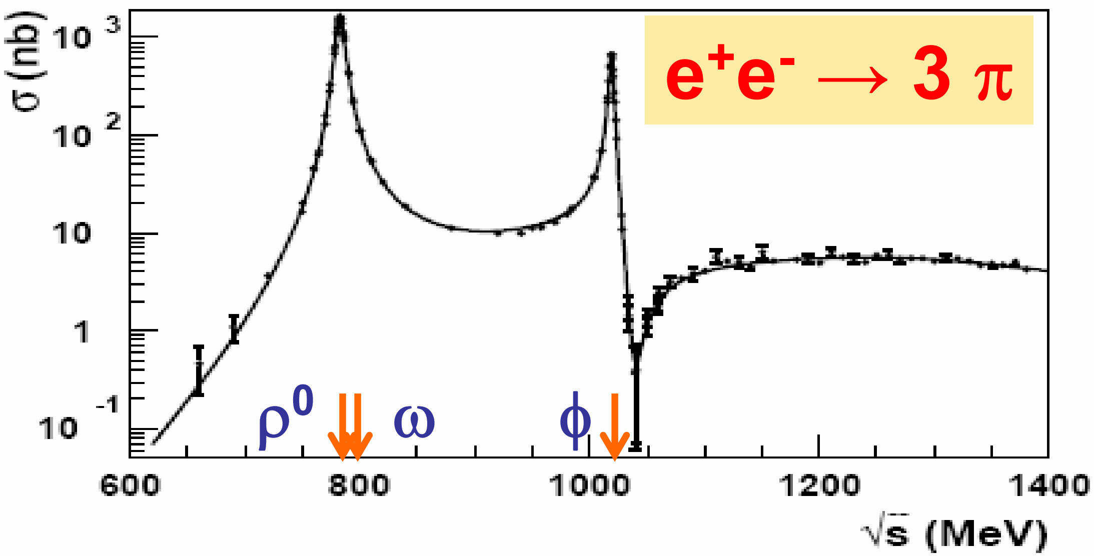


Figure 4. The $e^+e^- \to \pi^+\pi^-\pi^0$ cross section measured by SND [44,46,34]. The curve is the fit with the $\omega, \phi, \rho, \omega', \omega''$ resonances.

ρ-contribution here deforms ω-tails

(see later)

$\Gamma(\rho \to ee)$=**7.04** keV; $\Gamma(\omega \to ee)$=**0.60** keV

$\Gamma(\rho \to \eta\gamma)$ = **44.9** keV
$\Gamma(\omega \to \eta\gamma)$ = **4.1** keV
$\Gamma(\phi \to \eta\gamma)$ = **55.6** keV

$\leftarrow$ u, d subtraction

$e^+e^- \to \eta\gamma$

The ρ,ω peak has
break near m_ρ ,
while **max** near m_ω ,
despite the smaller ω–term.
Constructive **interference !**
(details see later)

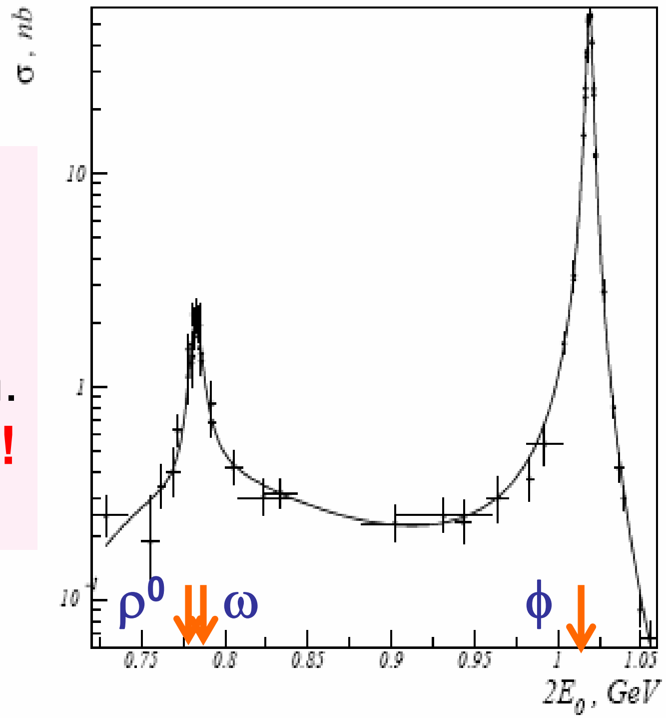


Figure 5: The measured cross section of the $e^+e^- \to \eta^0\gamma$ process, the curve is the best fit.

hep-ex/0512027

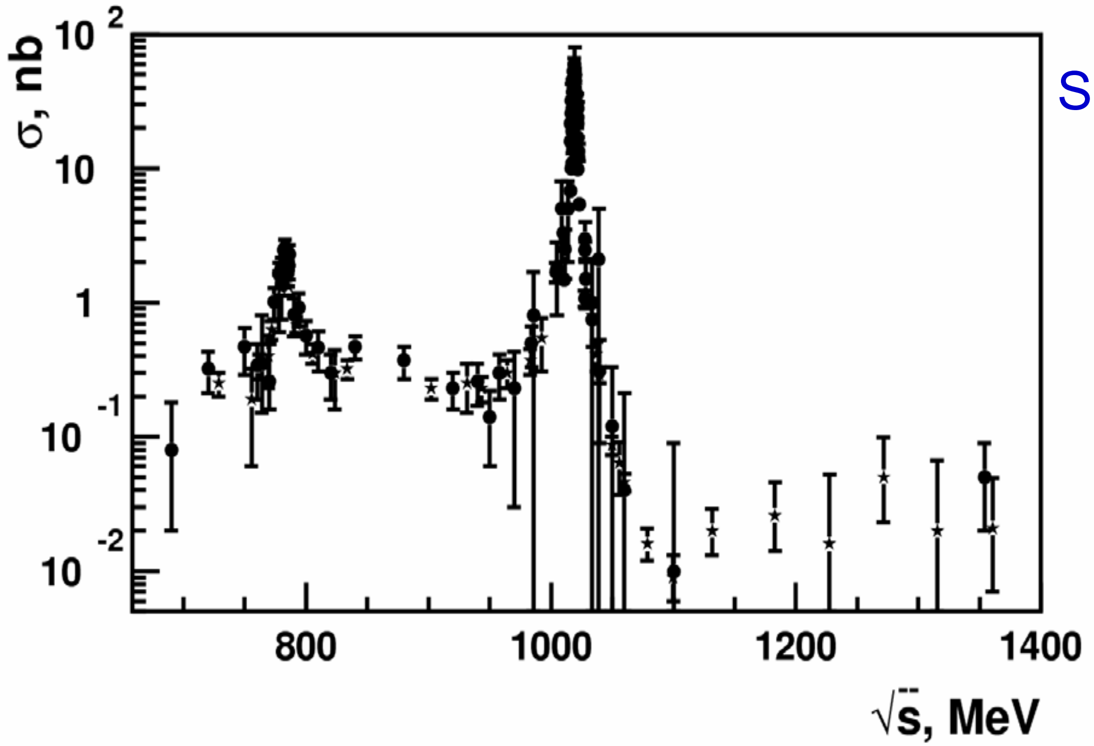
SND Collab.

The *right* side
of the ϕ –peak
is **sharper** than
the *left* one.

Interference ?

$e^+ e^- \rightarrow \eta \gamma$

hep-ex/0604051



SND, CMD2 Collabs.

Cross sections at the left and to the right of the narrow ϕ -peak are different.

Interference !

hep-ex/0604051

$e^+e^- \to \pi^+\pi^-$

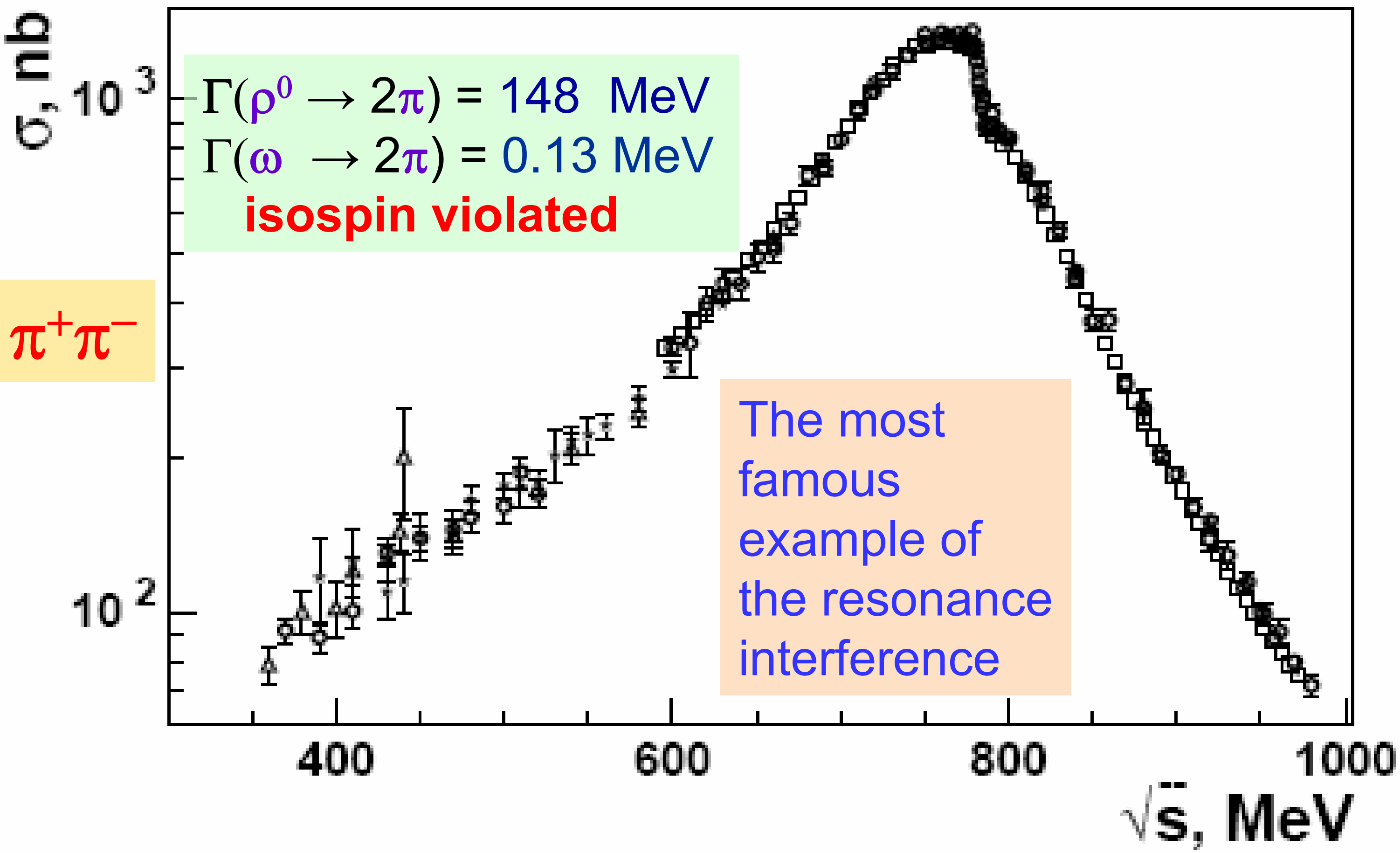


Figure 2. The $e^+e^- \to \pi^+\pi^-$ cross section. OLYA and CMD (△) [36], SND (⋆) [37], CMD-2 (○) [38,39,40] and KLOE (□) [5] data are shown.

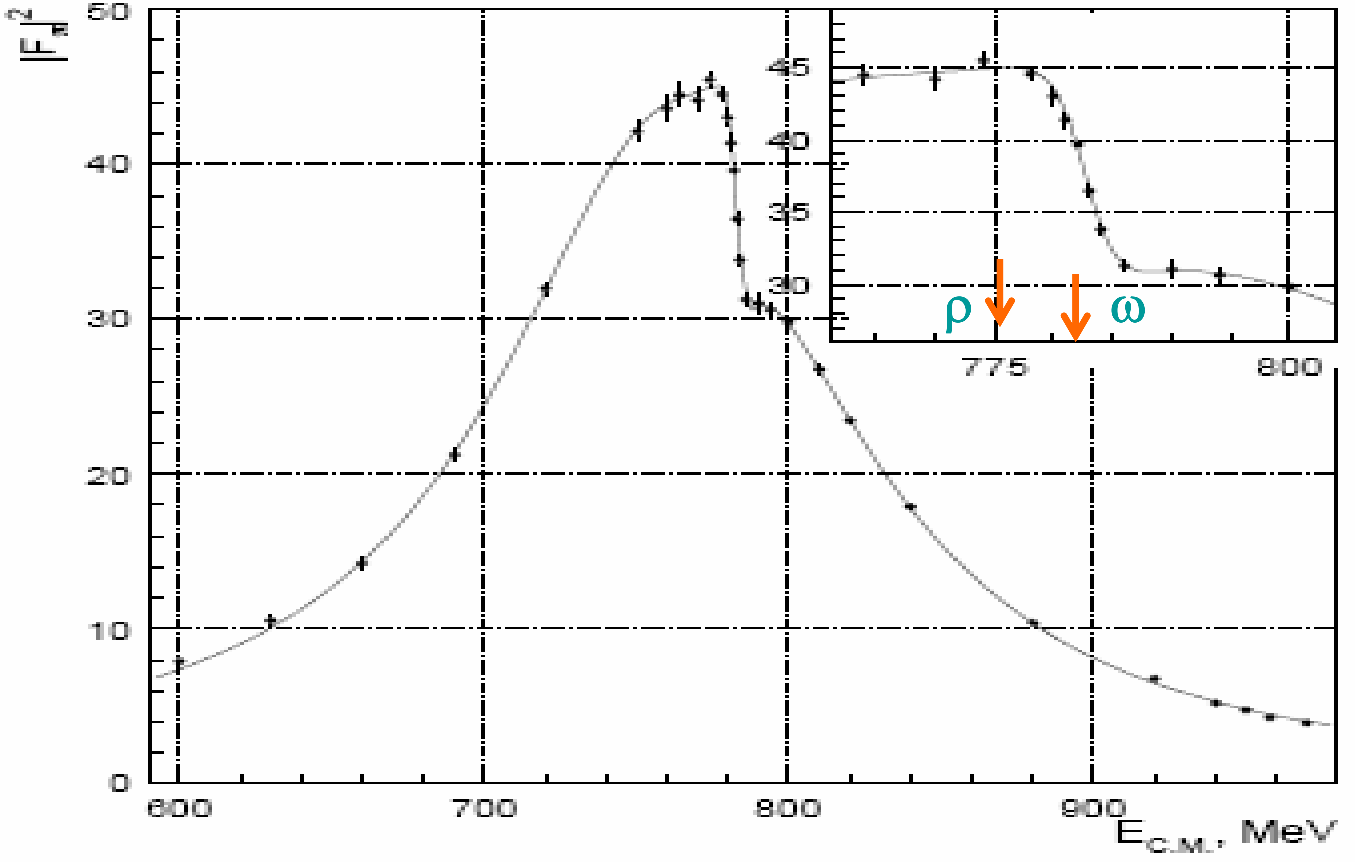


Figure 9: Fit of the pion form factor measured in this work

$e^+e^- \to \pi^+\pi^-$

hep-ex/0610021
CMD-2

interference
is the only
source
of information
on the decay
$\omega \to 2\pi$

Specifics of this case: rapidly decreasing "bkg" (ρ –peak) **;**
ρ–ω mixing may (and does) have complexity [Ya.A., EPJ A16 (2003)]
$\Rightarrow$ interference curve is strongly **asymmetric**: decrease, no increase.

The opposite relative sign would reveal additional peak (the case of $\eta\gamma$).

$\Gamma(\omega \to \pi^0\gamma)$ = 0.76 MeV
$\Gamma(\rho^0 \to \pi^0\gamma)$ = 0.09 MeV u, d subtraction
$\Gamma(\phi \to \pi^0\gamma)$ = 0.005 MeV **Zweig rule violated**

$e^+e^- \to \pi^0\gamma$

hep-ex/0512027

SND Collab.

Interference
of 3 vector mesons:
ρ^0, ω, ϕ

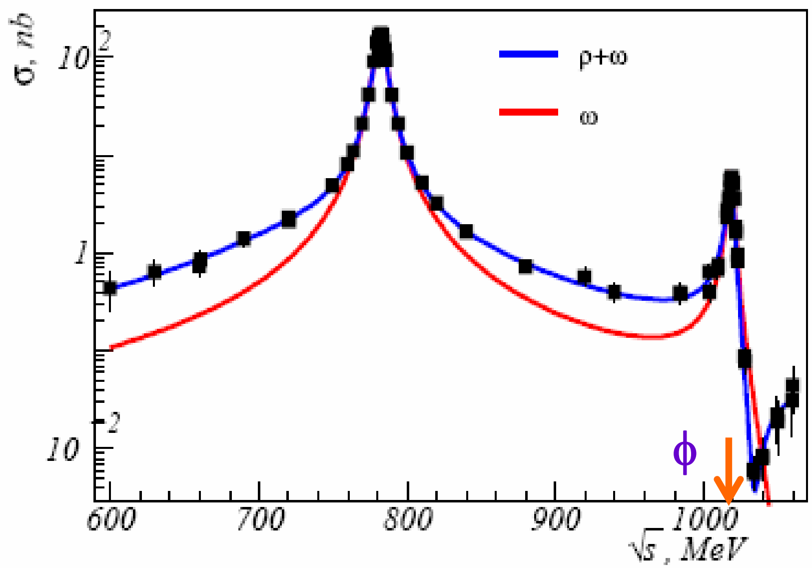


Figure 4: The measured cross section of the $e^+e^- \to \pi^0\gamma$ process, two fitting curves correspond to models with $\rho + \omega$ and ω intermediate states respectively.

Structure of the interference curve is qualitatively similar here to the case of 3π

$\phi \to \omega\, \pi^0$

doubly suppressed:

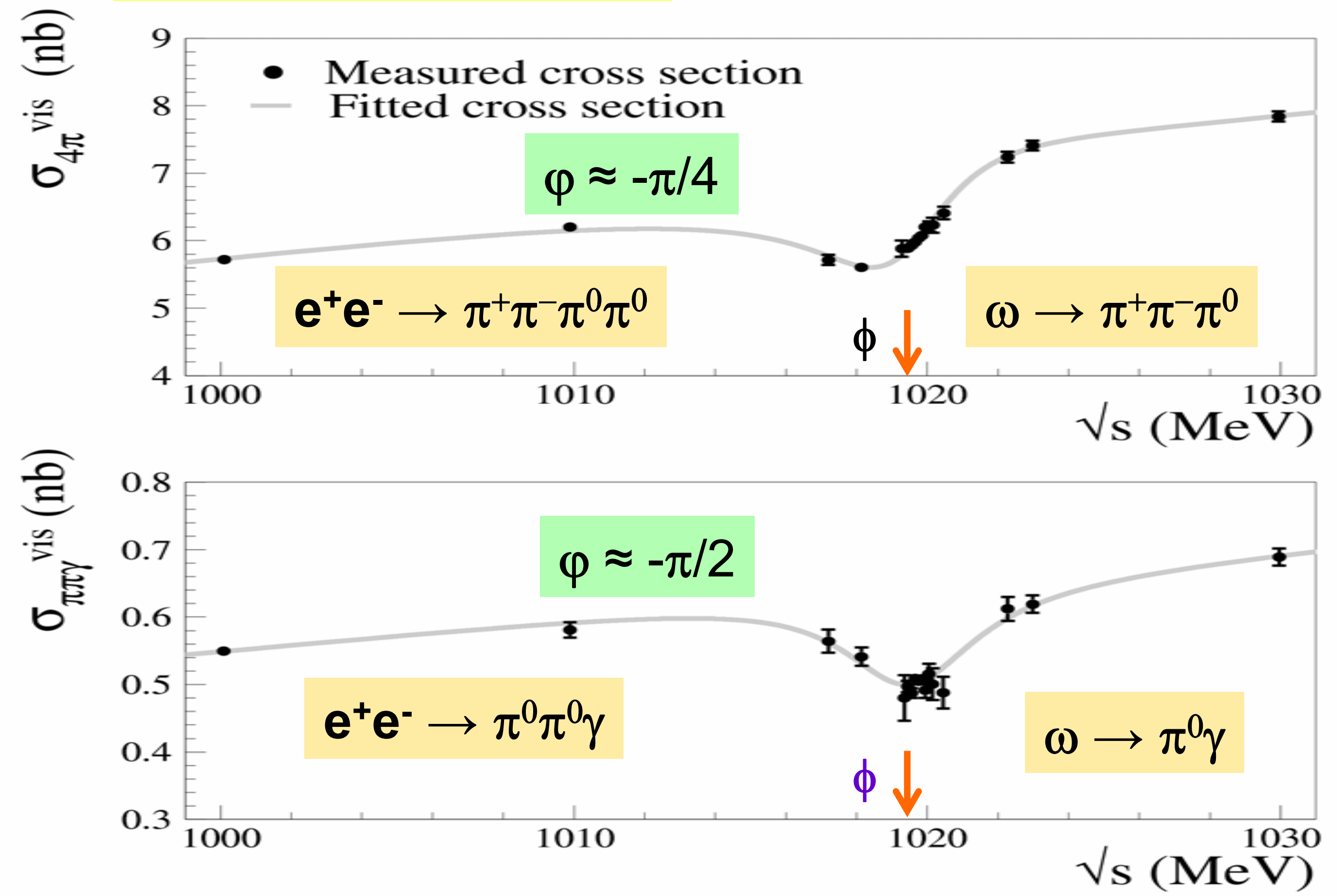
Zweig rule, isospin

arXiv: 0807.4909 [hep-ex]

KLOE Collab.

The two <u>different</u> **curves** have <u>different</u> **dip positions**,

because of <u>different</u> **relative complexity**



These data result in

Br($\phi \to \omega\, \pi^0$) = $(4.4\pm0.6)\times10^{-5}$;

Γ($\phi \to \omega\, \pi^0$) = 0.19 keV

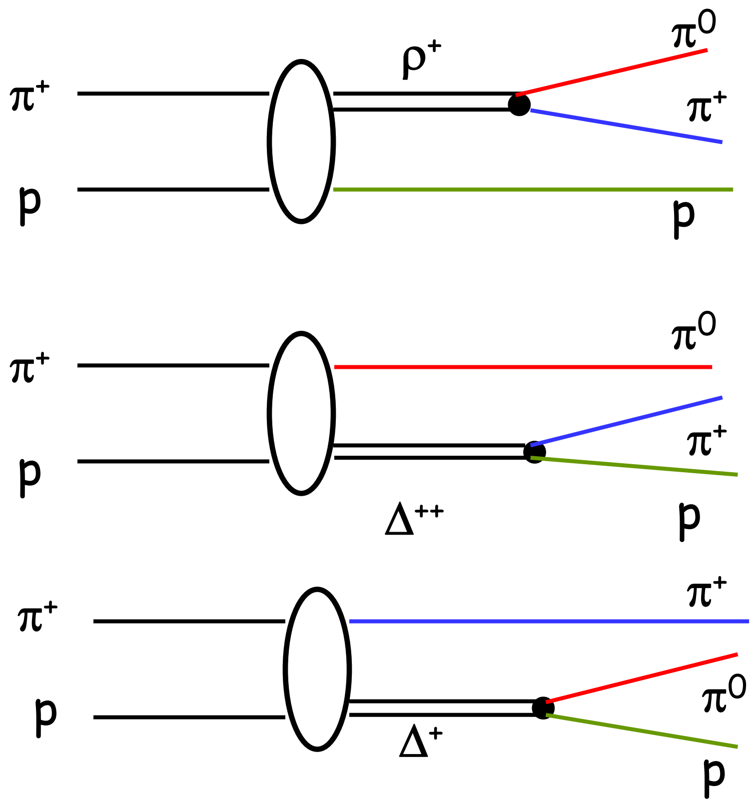
Intermediate conclusions (2)

- All the above examples demonstrate
  the direct interference of 2 resonances:
  all final particles can be decay products
  of any of the interfering resonances.
- Such a kind of interference appears very efficient
  to search for rare decays of known resonances.
  May strongly deflect a resonance manifestation
  from the familiar BW peak.
- There can be other kinds of interference,
  where only some of final particles may come
  from any of the 2 interfering resonances.

Rescattering interference

Different resonance configurations may produce the **same** state of 3 or more particles.
Such contributions are coherent and may **interfere**

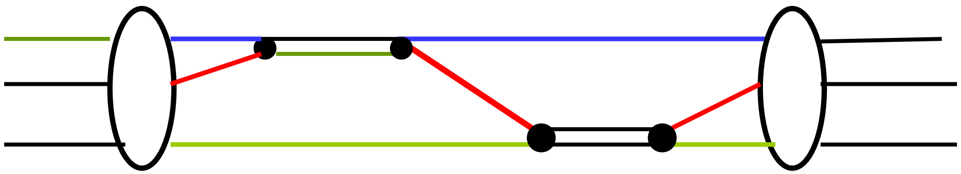
The contributions depend on energies and momentum transfers; may **shift and move** positions of bumps/dips



The phenomenon is known since 60s.
It was considered as **hindrance** to resonance studies.

This interference was usually (and is still now) cut away.

Rescattering interference



The name rescattering reflects similarity with the rescattering in 3-particle interactions:
one particle changes its interaction partner.

On the other side, this kind of interference is similar to the famous case of 2 quantum slits, since **one particle** refers **simultaneously** to **2 resonances**.

The resonances are in different **systems** and may have different **quantum numbers**, but final states, after resonance decays, should contain the same particles.

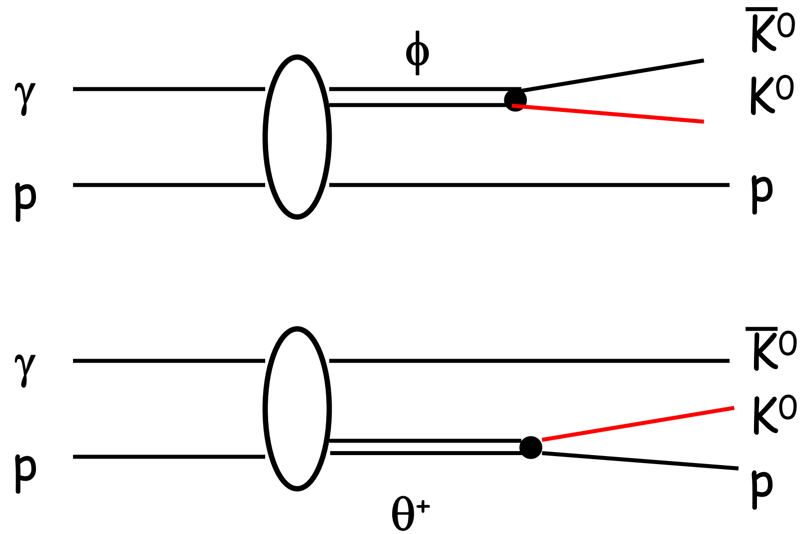
The 2 resonances **can interfere**, **only if** the final configurations are kinematically consistent.

→

This requires limited intervals of the **total energy** and **momentum transfers**

Positions of the interference bumps/dips, generally, depend on kinematic parameters and **move** with their changes (in difference with **true** resonance positions)

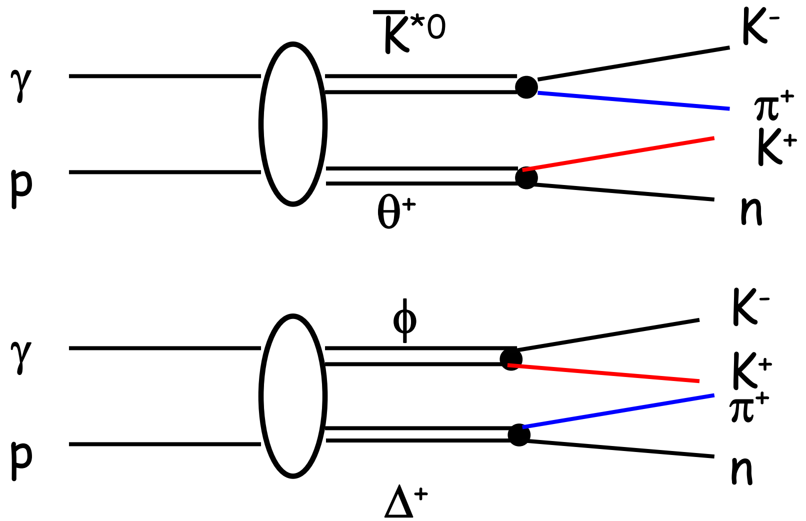
Direct interference of resonances has become an efficient **instrument** actively used to study rare decays of **known** resonanses.



Amarian, Diakonov, Polyakov (hep-ph/0612150) have suggested to apply the **rescattering interference** for revealing small **new** resonance signals (**amplification by interference with strong signal**).

The Θ -signal may indeed be small, if its production is a new kind of hard processes [Ya.A., Goeke, Strakovsky, PR D76 (2007)].

Final states with >3 particles admit more complicated cases of the rescattering interference



An example of the 4-particle rescattering interference that may enhance the small Θ^+-contribution (suggested by M.Amarian)

Summary

- Interference of resonances (in the energy representation) has the same origin as the known particle oscillations (in the space-time representation).
- A small resonance contribution may be amplified and revealed due to its interference with high background (e.g., another resonance).
- Manifestation of an interfering resonance may be very different: bump, or dip, or both; may depend on the decay mode. Positions of the bump/dip are, in general, shifted from the true position of the resonance.
- The form of the “resonance” curve essentially depends on properties of the background and on the Res-Bkg relative phase: it may be symmetric, or antisymmetric, or strongly asymmetric.

Summary (cont.)

- **Direct** interference is actively used now as an important instrument for resonance studies. Some rare decays of well - established resonances are known only due to interference manifestations.

- **Rescattering** interference of resonances may be very useful as well**:** to amplify small resonance signals, especially with new quantum numbers**;** to study production mechanisms of the known resonances.

- **Interference of resonances** looks to be worth of more detailed studies, both **experimental** and **theoretical**.